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# The Role of Ice Shelves in Antarctica, Ice Shelf Variation Across Antarctica and the Mechanisms Behind Ice Retreat

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Abstract (ca. 200 words):

Ice shelves are an important component of Antarctica, they restrict the flow of glaciers at the edge of the Antarctic Ice Sheet (AIS) therefore limiting any loss of ice from the ice sheet. Ice shelves across Antarctica are undergoing changes, mostly the retreat of ice. Iceshelf loss in Antarctica is mainly to be a result of basal melting and iceberg calving. As ice shelves act as barriers to the ice sheet, disintegration of ice shelves will have major consequences for the Antarctic Ice Sheet and for global ocean levels. This literature review analyses studies on the changes of ice shelves across Antarctica and the reasons for iceshelf variation.

**Contents**

## Introduction

Ice shelves float on top of the ocean and are formed by the Antarctic Ice Sheet (AIS) flowing to the iceshelf grounding lines, snow accumulation over many years and by basal freezing (Depoorter et al. 2013; Smethie & Jacobs 2005). Ice shelves play an important role in the stability of the AIS as they provide a barrier to prevent any loss from the ice sheet further up (Albrecht & Levermann 2014; Langley et al. 2014). More than 80% of Antarctica's grounded ice is drained out through ice shelves and the flow of glaciers is responsive to change of thickness and extent of ice shelves (Pritchard et al. 2012). Therefore the reduction in iceshelf mass could lead to acceleration of the loss of the AIS (Walker et al. 2015; Pritchard et al. 2012).

Ice shelves experience loss of mass by surface ablation, iceberg calving, and melting through the movement of circumpolar deep water into the cavity of ice shelves and through the mixing of tides and wind near the edge of the ice (Depoorter et al. 2013; Smethie & Jacobs 2005). These mechanisms contribute to the most amount of ice loss of the AIS (Walker et al. 2015). The loss of ice from melting at the base being the mechanism behind the greatest form of ice loss from ice shelves and decreases the thickness of ice shelves ((Alley et al. 2015; Arzeno et al. 2014). However, the upper layers of ice shelves are warmer than other areas of ice sheets and therefore can experience melting, if enough meltwater is present iceberg calving can occur through crevasses (Alley et al. 2014). Depoorter et al. (2013) suggest the main cause of ice loss from the Antarctic ice sheet occurs due to iceberg calving. It takes up to centuries for ice to flow from the grounding line where the flow of ice starts, to the edge of the ice where icebergs are calved. A small amount of warming is able to have a substantial effect of the thickness of an ice shelf and subsequently the mass of the AIS (Alley et al. 2015; Walker et al. 2015).

Winkelmann et al. (2012) suggest the onset of climate change will cause greater snowfall onto the Antarctic continent which will cause higher discharge of ice from the ice sheet in the future; this effect being greater than the loss from basal melting and surface melt.

## West Antarctica

### Ross Ice Shelf

The Ross Ice Shelf (RIS) is the Antarctica's largest ice shelf and is fed by streams coming from the West Antarctic Ice Sheet (McKay et al. 2008). McKay et al. (2008) analysed sediment cores from underneath McMurdo Ice Shelf and water north of Ross Island using radiocarbon dating to study changes in the RIS since the last glacial maximum. The study identified the retreat of the RIS during this time, with the grounding line retreating from the Drygalski Trough to the south of Ross Island around $8900^{14}$ C years BP. It was around this time that the RIS attached to Ross Island. The grounding line has continued to retreat since this time, but the calving front has remained in the same location. The report does not address any cause for more recent Ross Ice Shelf retreat.

Hulbe et al (2013) addressed recent changes in the RIS using data from surface velocities from 1973-78 to 2003/4 and 2008/9. The study found small acceleration in some areas and large slowing of the flow of the ice shelf. The speed of ice movement was slower in the 2003/4-2008/9 period than in 1973-78 and the slowest areas were around the grounding line next to the Whillans Ice Stream (WIS) and Mercer Ice Stream (MIS) which feed the iceshelf. The study investigated thickness of the Ross Ice Shelf, determining thickening has occurred in places closer to the grounding line near the WIS and the MIS, and at middle of the ice shelf. Thinning had taken place around the front of the iceshelf during the period studied. It is suggested that the flow at the front of the iceshelf has increased due the thicker ice from the WIS moving down-stream. Whereas the slowing of the WIS which feeds into the RIS is due to a continual movement of boundary change; possibly due to high traction underneath the iceshelf. A study by Smethie & Jacobs (2005) used chlorofluorocarbon (CFC) data collected from the Ross Sea in the summers of 1984, 1994 and 2000. The aim was to identify CFC uptake by the ocean, which was then combined with salinity measurements to identify the production of Ice Shelf Water (ISW) to determine the production of ISW under the Ross Ice Shelf. High Salinity Shelf Water (HSSW) becomes fresh when converting to ISW due to melting, the study found the net rates of melting were greater than the net rate of cooling of the HSSW. The study did not specify what the cause of the large variation in melting and cooling rates was.

## Antarctic Peninsula

The Antarctic Peninsula has undergone disintegration of ice shelves in recent decades as a result of atmospheric and ocean warming of the area, this has led to the thinning of the glaciers that feed these ice shelves and thinning of ice shelves themselves (Holt, Glasser & Quincey 2013). Dinniman, Klink & Smith (2011) found the West Antarctic Peninsula undergoes basal melting due to an influx of warm Circumpolar Deep Water (CDW) underneath ice shelves, this water experiences little vertical mixing and therefore warm water becomes in contact with the bottom of the iceshelf. The incursion of this warm water was estimated to occur frequently, approximately 2-3 times a month, and did not exhibit a seasonal pattern. Short-term wind events were suggested as a partial cause of this influx. Wilkins Ice Shelf is located on the west Antarctic Peninsula, Padman et al. (2012) convey that in 2008 and 2009 the iceshelf underwent significant calving losing an area of approximately 425 km$^2$. The study also evaluated changes in the ice shelf from 1992 to 2008 and found iceshelf thinning as a result of basal melt. The study states the ice shelf is thinner than some other ice shelves as mechanisms of upper ocean wave action have an effect on basal melting, which occur in shorter time periods. This influx of warm water has led to basal melting, the Antarctic Peninsula is the area of Antarctica prone to warmer conditions and this is showing to have an effect on ice shelves in this region.

## Larsen Ice Shelf

The Larsen Ice Shelves are situated along the east coast of the Antarctic Peninsula and have shown dramatic retreat in past decades. In 1995 part of the Larsen Ice Shelf named the Larsen A Ice Shelf disintegrated, also that year the Larsen B Ice Shelf went through significant calving (Rott et al. 2002). In 2002 the Larsen B Ice Shelf nearly completely disintegrated, this was attributed to meltwater on the surface of the iceshelf as a result of high atmospheric temperature (Padman et al. 2012). A small section of the iceshelf was left after the collapse, only small acceleration in the flow of glaciers leading into this ice shelf have been noted (Rott et al. 2002). However, Holland et al. (2015) states the disintegration of both the Larsen A and B Ice Shelves have caused an increase in the flow of their adjacent glaciers and therefore adding to sea level rise. The Larsen C Ice Shelf (LCIS) is the last remaining ice shelf in the north Antarctic Peninsula. A rift in this iceshelf has been present since 2010 and increased quickly in 2014. The iceshelf is suggested to be unstable due to this rift and it is expected the rift will cause calving events in the future (Jansen et al. 2015). Luckman et al. (2015) convey that surface melt on the LCIS is occurring. This is a result of fohn, a process where warm westerly winds move into an area therefore warming it, this mechanism has intensified during the last 50 years due to a positive phase of the Southern Annular Mode. It is possible for these melt pools to extend deeper into the iceshelf causing fractures to occur in the ice and weakening the iceshelf. Holland et al. (2015) states the surface of the LCIS has lowered from 1998 to 2012, this is attributed equally to the loss of ice and firn air, the air compacted within the ice. The study suggests the ice loss may be a result of basal melting and the air loss by surface melt or ice compaction. Jansen et al. 2010 outline the LCIS is stable in current conditions, however, just as the Larsen A and B Ice Shelves have disintegrated, the LCIS may also be subject to mass loss and weakening in the future and be subject to the threat of disintegration as well. The Larsen Ice Shelves location on the Antarctic Peninsula have exposed them to warm conditions and this effect has been revealed on numerous occasions in respect to ice shelf disintegration.

## Amundsen Sea

The Amundsen Sea area has undergone some of the fastest ice loss from ice shelves around Antarctica (Paolo, Fricker & Padman 2015). Zhang et al. (2014) describe changes in ice shelves in the Amundsen Sea from 2004 to 2008. The Pine Island Glacier exhibited a volume loss of 0.2km $^3$ in one year and continued to lose mass over the preceding years. The area of ice of the iceshelf near the grounding line also decreased, which is the area in which the Pine Island Glacier flows into. This indicates that the decrease in iceshelf thickness reduces buttressing and leads to an increase in glacier movement and will potentially increase ice loss from the Antarctic Ice loss. Although an iceberg calved from the front of the iceshelf in 2007, inducing ice shelf retreat. Muto, Anadakrishnan & Alley (2013) outline the Pine Island Glacier has been undergoing mass loss over the past two decades. The movement of warm CDW was revealed as causing melting underneath the Pine Island Glacier Ice Sheet. Thoma et al. (2008) distinguish westerly winds were the cause of the increased influx of warm CDW water around the Pine Island Glacier Bay region. The Amundsen Sea has been a hotspot for iceshelf retreat in Antarctica, the mechanisms of basal melting and iceberg calving noted here are behind this retreat.

Ice Shelves in the Amundsen Sea have undergone thinning and this has had subsequent effects on adjacent glaciers. Zhang et al. (2014) also analysed the Getz Ice Shelf and found the iceshelf only experienced small changes. Limited changes were established as a result of the ice shelfs proximity to multiple islands which limit the flow of the iceshelf. However, Paolo, Fricker & Padman (2015) observed ice shelves in the Amundsen Sea from 1994 to 2012 and found over this time the Getz Ice Shelf lost 6% of its mass. Part of the study by Zhang et al. (2014) was focused on the ice shelves in front of the Thwaits, Smith and Pope Glaciers, these ice shelves revealed consistent thinning over the period studied. The iceshelf next to the Thwaits glacier exhibited thinning near the front of the iceshelf, and therefore did not have much of an effect on glacier loss. However, the Thwaits Glacier was undergoing elevation decrease itself and therefore was undergoing volume loss. It was concluded that the iceshelf in front of the Smith and Pope Glaciers was fragmented and therefore were not as effective at restricting loss of ice from these glaciers. This means ice loss from the Antarctic Ice Sheet may increase in this area as a result of a weakened buttressing effect. The study concluded that in the Amundsen Sea basal melt due to warm water upwelling is the greatest form of iceshelf loss, with the grounding line being particularly impacted. As shown in these examples the effect of iceshelf retreat can vary due to the location of retreat and therefore affect the movement of glaciers and the Antarctic Ice Sheet differently.

Bellingshausen Sea

Ice Shelves in the Bellingshausen Sea have been shown to experience significant ice loss. Paolo, Fricker & Padman (2015) observed ice shelves in the Bellingshausen Sea from 1994 to 2012 and found a loss of 5% of the ice shelves due to thinning. The Venable Ice Shelf exhibited the greatest decrease in thickness out of eight sites surveyed in the Amundsen and Bellingshausen seas, losing 18% of its ice which foresees a total loss of the iceshelf in 100 years. Holland, Jenkins & Holland (2010) investigated the George VI Ice Shelf in the Bellingshausen Sea from 1979 to 2007 and established the iceshelf had been melting throughout the observation period. The study found interannual variability in melting with most due to activities at the south of the iceshelf. Surface mechanisms of water mixing on the continental shelf were found to regulate the amount of heat reaching the iceshelf. Kimura, Nicholls & Venables (2014) calculated a net melt rate of approximately 1.4m/yr$^{-1}$ for the George VI Ice Shelf. The study observed thermohaline staircases beneath the iceshelf and found heat and salt fluxes in the sea water matching the melting rate of the iceshelf. Ice shelves in the Bellingshausen Sea have been revealed to undergo thinning, this is in an area of Antarctica which is warming significantly.

**East Antarctica**

Amery ice shelf

Studies conducted in East Antarctica have shown basal melting to contribute to 50% of the melting of an iceshelf. Wen et al (2010) investigated basal melting and freezing of the Amery Ice Shelf using data from the late 1990s to the early 2000s. The study found that basal melting contributes to half of the total ice loss from the ice shelf, with the highest amount of melting taking place near the grounding line of the iceshelf. The study found that the net melt of ice exceeded the net freeze of water under the iceshelf, with total net melt at 46.46.9 Gt $a^{-1}$. The study outlined that the influx of warm water occurring seasonally, tidal movement and the temperature difference between the sea water and the temperature at which sea water freezes at deeper depths contributed to the basal melting of the iceshelf. Fricker et al (2005) conducted a study of the Amery Ice Shelf from 1996 to 2004 using satellite imagery. The study found two rifts in the ice shelf close to the calving area were propagating, with rates greater in the austral summer. A study carried out by Walker et al. (2015) on five rifts on the Amery Ice Shelf from 2002 to 2014 came to similar conclusions. The rifts showed lengthening throughout the study, propagation occurring mostly in summer, most propagation occurred in random, large segments and each rift lengthening at its own rate. The two rifts lengthening westwards showed to increase its propagation rate throughout the study, however, the three eastward lengthening rifts revealed slowing after 2010. The study did not find a mechanism behind these propagation events and ruled out any correlation between environmental conditions to increased propagation rates as large propagation events for different rifts occurred.

The Fimbul Ice Shelf in East Antarctica has exhibited basal melting. Basal melt rates of the iceshelf were identified by Langley et al. (2014) using an interferometric radar during December 2009 and 2010. Flat and shallow regions of the ice shelf experienced low rates of basal malting while greater melt rates occurred in thicker areas. This ratio corresponds with water temperature being near the freezing point at the water’s surface and deeper water experiencing warmer temperature. However, high melting also occurred at the edge of the iceshelf which is a result of the movement of the coastal current next to its edge. The study outlined that there was a seasonal difference in melting rates, that being higher in the summer, but did not identify a large temporal difference. A melt rate of 1m/year was calculated for the Fimbul Ice Shelf, a low melt rate, and was determined as a result of ocean currents and movement of water underneath the iceshelf. Basal melting contributes to a large degree of iceshelf retreat, different areas of ice shelves may experience varying amounts of ice loss, this melting is determined by ocean conditions in certain areas.

**Conclusion**

Antarctic ice shelves are losing mass and this is occurring at numerous rates at different locations. There are multiple mechanisms behind the reduction in ice of ice shelves. Basal melting and iceberg calving represent the two mechanisms behind the greatest amount of ice loss, however, surface melt also has as a role in iceshelf disintegration. Despite the numerous causes of iceshelf disintegration, the melting of ice into the ocean will affect the conditions and volume of the water in the earth's oceans. If ice shelves diminish around the coast of Antarctica there will be ramifications for the Antarctic Ice Sheet. Further research could be carried out to determine ice shelf changes in areas not commonly studied and how climate change will affect ice shelves and the Antarctic Ice Sheet in the future.

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